Master thesis R.J. van der Ent

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Ruud van der Ent
A new perspective on continental moisture recycling

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Abstract
The importance of moisture feedback between continental precipitation and evaporation, referred to as moisture recycling, is still under debate. Most of the research in the past focused on the contribution of recycling to precipitation within a certain region only. This paper clearly distinguishes between different definitions of moisture recycling. This allows us to study the complete process of continental moisture recycling. In addition to identifying how much of the precipitation originates from continental sources, a new definition is used to identify regions which are major moisture suppliers for continental precipitation. An accounting procedure based on ERA-40 reanalysis data is used to calculate moisture recycling ratios. As such, this paper derives new information from existing data. It is estimated that on average 38% of the continental precipitation has continental origin and that 52% of the continental evaporation returns as precipitation over continents. This paper demonstrates the important role of topography in the Andes and the Tibetan Plateau where regional moisture recycling is a key process. The Amazon and the Congo are identified as very important regions for sustaining continental precipitation. It is also demonstrated that moisture recycling from the Eurasian continent is the major supplier of the fresh water resources of China.

1 Introduction: do we know how continental precipitation and evaporation interact?
This paper aims to give more insight into the importance of feedback between continental precipitation and evaporation, referred to as moisture recycling. The significance of moisture recycling is an indicator of the climatic sensitivity to land-use changes. Continental evaporation is the only moisture flux humans can influence directly through land-use changes. To study the potential impact of these land-use changes on our fresh water resources it is therefore important to know the significance of continental evaporation. In general, evaporation is enhanced by reducing runoff (e.g. by constructing dams and reservoirs) or by leading runoff back onto the land (e.g. by irrigating on previously bare soil). Conversely, evaporation is reduced by enhancing drainage (e.g. by cutting forest and overgrazing).

The scientific view on the contribution of continental evaporation to continental precipitation is still under debate and the mainstream views have changed over time. Early studies on moisture recycling focused on the continental landmass of North America. Aughey (1880, as cited in Eltahir and Bras (1996)) wrote about the physical geography of Nebraska, "year by year as cultivation of the soil is extended, more of the rain that falls is absorbed and retained to be given off by evaporation or to produce springs. This of course must give increasing moisture and rainfall." It is the basis of legends such as the belief that "rain follows the plow", as cited in Dirmeyer and Brubaker (2007).

The idea that the contribution of evaporation from a land region to precipitation in the same region is significant was widely accepted until the late 1930’s. This theory was later criticised and different estimates claimed the opposite (Benton et al., 1950, McDonald 1962, as referred to in Brubaker et al., (1993)). Studies performed with the classical formulas of Brubaker et al. (1993) and Eltahir and Bras (1994) largely supported the point of view that moisture recycling is not significant (see e.g. Trenberth, 1999 and Szeto, 2002), while studies with the formulas of Savenije (1995) and Schär et al. (1999) indicated that moisture recycling is indeed more significant. A comparison of the results from applying different formulas was made by Mohamed et al. (2007). Recent studies pointed out that the classical methods of Brubaker et al. (1993) and Eltahir and Bras (1994, 1996) may underestimate precipitation recycling, because of the assumptions made in the modelling approach (e.g. a constant and parallel
moisture flux over the study region). These studies also developed methods to relax the modelling assumptions (Burde and Zangvil, 2001a, 2001b, Burde, 2006, Burde et al., 2006, Dominguez et al., 2006 and Fitzmaurice, 2007). Many of the recent methods that were developed to estimate moisture recycling (e.g. Stohl and James, 2005, Bosilovich and Chern, 2006, Dirmeyer et al., 2007 and Liu et al., 2008) indicated that continental evaporation can be a significant contribution to continental precipitation.

The lack of consensus on the importance of moisture recycling is not only caused by the use of different estimation methods, but for a large part by the use of different definitions. Until now, most research focused only on the question of whether precipitation is recycled within a certain region, such as a river basin (e.g. Eltahir and Bras, 1994, Brubaker et al., 2001, Szeto, 2002, Serreze and Etringer, 2003, Burde et al., 2006, Mohamed, et al., 2005, 2007 and Kunstmann et al., 2007), grid cells of a certain dimension (Trenberth, 1999, Dominguez et al., 2006 and Dirmeyer and Brubaker, 2007) or other large regions (e.g. Brubaker et al., 1993, Schär et al., 1999 and Bisselin and Dolman, 2008, 2009). Such studies provide information on the importance of evaporation for the occurrence of precipitation within that same region, but say little about all sources of precipitation.

Studies that clearly made the distinction between continental and oceanic sources were performed by Savenije (1995, 1996a, 1996b) and several others, who identified the contribution of different continental and oceanic source regions to precipitation in a certain study region to describe the precipitation recycling (Koster et al., 1986, Druyan and Koster, 1989, Numaguti, 1999, Bosilovich and Schubert, 2002, Bosilovich, et al. 2002, Yoshimura et al., 2004, Stohl and James, 2005, Bosilovich and Chern, 2006 and Nieto et al., 2006, 2007, 2008). To our knowledge, only the studies of Bosilovich et al. (2002) and Yoshimura et al. (2004) presented a global map of precipitation recycling which distinguishes between continental and oceanic sources. The latter two studies identified the areas on the globe where a large part of the precipitation consists of continentally recycled moisture. According to these studies, a substantial part of the precipitation falling in the north-east of North America, the west of South America, central Africa and large parts of Siberia, Mongolia and China consists of moisture that evaporated from any continental area rather than the ocean.

This paper identifies the regions where precipitation is largely dependent on moisture recycling. Moreover, it shows which regions are major suppliers of continental precipitation. As such, this paper yields new insight in the continental moisture feedback process. The outline of the paper is as follows. Section 2 explains the methods used in this study. It describes the (new) definitions used in this paper. It presents the input data used and provides a schematisation of the accounting model. The assumptions and limitations of our method are discussed. Section 3 presents the results of the study. It shows why scale-dependent regional recycling ratios are not sufficient to show the full moisture recycling processes. On a global map, the annual average continental sources and sinks for precipitation are identified. The typical winter and summer moisture cycling is discussed by continent. Section 4 concludes with a discussion of where and in what way moisture recycling plays an important role in sustaining precipitation. The implications of the results on water resources management are discussed. Finally an outlook is given on further research.

2 Methods

2.1 Definitions

To bring clarity in the discussion on whether continental precipitation and evaporation feedback is important in a certain region, we distinguish different types of moisture recycling. The process that is most commonly referred to in the literature as moisture or precipitation recycling is defined in this paper as regional precipitation recycling. It is the part of the precipitation in a region which originates from evaporation in the same region. This definition is scale-dependent. The precipitation is considered to consist of two components:

$$P(t, x, y | A, \Delta) = P_r(t, x, y | A, \Delta) + P_o(t, x, y | A, \Delta)$$

(1)

where $P_r$ is regionally recycled precipitation and $P_o$ is precipitation which originates from moisture that was brought into the region through advection. The regionally recycled precipitation in this case depends on time $t$ and location $(x,y)$, given an area size $A$ and shape $\Delta$. The corresponding regional precipitation recycling ratio is defined as:

$$\rho_r(t, x, y | A, \Delta) = \frac{P_r}{P}$$

(2)
This ratio describes the region’s dependence on evaporation within the region to sustain precipitation. Note that \((x,y)\) indicates the location of the region. In addition, we define the reverse process: how much of the evaporated water returns as precipitation in the same region (the regional evaporation recycling). Hence, the total evaporation in a region is described by:

\[
E(t, x, y | A, \Delta) = E_r(t, x, y | A, \Delta) + E_a(t, x, y | A, \Delta)
\]

where \(E_r\) is the part of the evaporation from the region which returns as precipitation in the same region and \(E_a\) is evaporated water that is advected out of the region. Averaged over a year \(E_r\) equals \(P_r\) (assuming no substantial change in atmospheric moisture storage over a year):

\[
E_r\text{(year, }x, y | A, \Delta) = P_r\text{(year, }x, y | A, \Delta)
\]

Similarly to the regional precipitation recycling ratio, the regional evaporation recycling ratio depends on the shape \((\Delta)\) and size \((A)\) of the region and is thus scale-dependent. It is defined as:

\[
e_r\text{(year, }x, y | A, \Delta) = \frac{E_r}{E}
\]

Comparing regional recycling ratios from various studies or areas has proven to be difficult because of its scale-dependency. Potentially, the relationship between the regional recycling ratio and area size could indicate typical travel distances of atmospheric moisture and thus the length scale over which precipitation and evaporation interact. Various attempts were made to approximate the relation between region size and regional precipitation recycling ratio by either a power law (Eltahir and Bras, 1996 and Dirmeyer and Brubaker, 2007) or a logarithmic function (Dominguez et al., 2006 and Bisselink and Dolman, 2008). However, the overall validity of these approximations is limited by the very nature of the regional precipitation recycling ratio which requires it to vary between zero and one, whereas these functions have no upper limit.

Moreover, regional recycling ratios depend not only on a region’s size but also on its shape. Imagine the case where a study region would be reduced to a long east-west oriented strip of only a few kilometres in width. In this case, even the slightest meridional moisture flux would result in calculated regional recycling ratios close to zero. Consequently, regional recycling ratios are inadequate to assess the importance of continental moisture feedback.

It is also possible to use local moisture recycling ratios which indicate the moisture recycling at a certain point \((x,y)\) embedded in a larger mother region \((x,y,A,\Delta)\) (e.g. Burde et al., 2006, Fitzmaurice, 2007 and Bisselink and Dolman, 2008, 2009). Typically these are used to calculate regional moisture recycling ratios for larger areas than the model grid. Although local moisture recycling ratios can be useful if one is interested in the recycling within a politically or hydrologically boundary, a local recycling ratio is not a natural characteristic. It suffers from being artificial due to the arbitrary choice of shape and size of the mother region and hence is not further used in this study. Instead, we use a mother region that consists of all continents together. This natural choice allows us to define scale- and shape-independent moisture recycling ratios. Hence, the precipitation at a certain location \((x,y)\) consists of two components:

\[
P(t,x,y) = P_c(t,x,y) + P_o(t,x,y)
\]

where \(P_c\) denotes precipitation which has continental origin (i.e. most recently evaporated from any continental area) and \(P_o\) is precipitation which has oceanic origin (i.e. most recently evaporated from the ocean). The corresponding continental precipitation recycling ratio is defined as:

\[
\rho_c(t,x,y) = \frac{P_c}{P}
\]

This ratio shows the dependency of precipitation at a certain location \((x,y)\) on upwind continental evaporation to sustain precipitation as a function of time \(t\). Similarly to the case of regional moisture recycling, we can define continental evaporation recycling. Here the evaporation is considered to consist of two components:
\[ E(t, x, y) = E_c(t, x, y) + E_o(t, x, y) \]  

(8)

where \( E_c \) is continental evaporation recycling that returns as continental precipitation and \( E_o \) is continental evaporation that is advected to the oceanic atmosphere and precipitates there. Note that the total annual \( E_c \) equals the total annual \( P_c \) (assuming no substantial change in atmospheric storage over a year). It is a special case of Eq. (4) where the region \( \{x,y,A,\Delta\} \) equals all continental areas:

\[
\iint_{\{x,y\} = \text{continental areas}} E_c(\text{year}, x, y) \, dx \, dy = \iint_{\{x,y\} = \text{continental areas}} P_c(\text{year}, x, y) \, dx \, dy
\]  

(9)

Finally, the continental evaporation recycling ratio at a certain location \((x,y)\) is defined as the ratio between continental evaporation that returns as precipitation on continents and total evaporation:

\[ \varepsilon_c(t, x, y) = \frac{E_c}{E} \]  

(10)

This ratio indicates the importance of evaporation at a certain location \((x,y)\) to sustain downwind precipitation in a given time period \(t\). Both continental moisture recycling ratios Eqs. (7) and (10) can be seen as a typical characteristic of a certain location and, in contrast to the regional moisture recycling ratios Eqs. (2) and (5), they do not suffer from scale- and shape-dependency of the study region. In Sect. 3.2 and 3.3 the combination of the precipitation and evaporation recycling ratio will prove to be a powerful tool to describe the global hydrological moisture cycle.

2.2 Data

Most of the meteorological input data are taken from the ERA-40 reanalysis\(^1\) (Uppala et al., 2005). We have used specific humidity, zonal and meridional wind at the lowest 13 pressure levels (100 – 1000 hPa), precipitation and total evaporation. We have chosen to use freely available data only; since the surface pressure field from the ERA-40 reanalysis is not publicly available we took the surface pressure field from the NCEP/NCAR reanalysis\(^2\) (Kistler et al., 2001). All reanalysis data is provided on a 2.5° latitude × 2.5° longitude grid with a temporal resolution of 6 hours.

The land sea mask of the ERA-40 reanalysis has been used to distinguish between continent and ocean. Grid cells with a sea mask which in nature have no connection to the ocean, such as the North American Great Lakes and the Caspian Sea, are considered a part of the continent in this study. We have used the data between the latitudes 55° S – 77.5° N, covering all continents except for Antarctica. Moreover, the data used cover the period of January 1997 – August 2002. After about a month reasonable model results have been obtained, but in total the period of January 1997 – August 1997 is used to spin up the model. Consequently, the results presented in Sect. 3 cover the period of September 1997 – August 2002, which is precisely five years.

The atmospheric moisture flux is typically highest in the range between the ERA-40 reanalysis 850 and 925 hPa pressure levels. This is due to strong winds and relatively high specific humidity as illustrated in Fig. 1. The topography of the study area and the annual average wind field in the 850-925 hPa pressure range is shown in Fig. 2. It can be observed that the moisture flux on the Northern Hemisphere from 30° N up to higher latitudes is mainly eastward, whereas the main moisture flux between 30° S – 30° N is westward. At latitudes lower than 30° S, the main moisture flux is again eastward but few continental areas are present at this latitude. Locally, these directions are disturbed by the presence of mountain ranges. For example, it can be seen that the Rocky Mountains in North America and the Great Rift Valley in Africa are blocking oceanic moisture from entering the rest of the continent. The opposite is true in South America where the Andes are blocking moisture from leaving the continent.

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\(^1\) ERA-40 reanalysis is data provided by the European Centre for Medium-Range Weather Forecasts (ECMWF), Reading, west of London, United Kingdom, from their Web site at [http://www.ecmwf.int/](http://www.ecmwf.int/)

\(^2\) NCEP/NCAR reanalysis is data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at [http://www.cdc.noaa.gov/](http://www.cdc.noaa.gov/)
Hereby, creating favourable conditions for moisture recycling. Figure 3 shows the annual average precipitation and evaporation as calculated from the ERA-40 dataset. The expected variability in precipitation and evaporation between tropical, desertlike and moderate climates is clearly discernible, as is the impact of mountain ranges on precipitation.

2.3 Accounting model

Essentially, the approach used is not a process model but a water accounting procedure, requiring the type of input data described in Sect. 2.2. It is based on the 2.5° x 2.5° grid on which all reanalysis data are provided. These grid cells have been approximated by trapezoids. The input data, which is on a 6-hour temporal resolution, has been reduced to a new dataset with a 1-hour resolution to reduce the Courant number, modelling on a 6-hour resolution raised problems with atmospheric moisture fluxes being several times larger than the atmospheric moisture storage at the previous time step. The land sea mask has been used to distinguish between continental cells with continental evaporation, and oceanic cells with oceanic evaporation.

A schematic of the accounting procedure is shown in Fig. 15 in Appendix A. The first step is qualitatively schematised in Fig. 1. Integrating the specific humidity between any two pressure levels yields the partial atmospheric moisture storage between those levels. Note that ERA-40 pressure levels with a higher pressure than surface pressure have been disregarded. The atmospheric storages between any two pressure levels are multiplied by the zonal and meridional wind velocities yielding partial horizontal moisture fluxes between any two pressure levels. Summing all partial fluxes yields the vertically integrated zonal and meridional moisture fluxes. By definition, integrating specific humidity over the vertical, as was also done by all similar studies that included atmospheric storage based on reanalysis data, neglects liquid water and ice in the atmosphere.

The atmospheric water balance equation gives the atmospheric moisture storage at the subsequent time step. The atmospheric moisture storage can also be calculated statically by simply integrating the specific humidity over the complete vertical. The result from the water balance and the integration of the specific humidity are not always equal. To close the water balance a residual factor is introduced to account for the difference between the atmospheric moisture storage calculated statically and from the water balance. Dominguez et al. (2006) and Bisselink and Dolman (2008, 2009) give a qualitative and quantitative assessment of this residual factor.

The next step in the modelling approach is to keep account of the composition (different origins) of precipitable water; this is illustrated in the lower half of Fig. 15 in Appendix A. The crucial assumption is that the moisture is well mixed over a grid cell and the vertical within a time step. Consequently, it is possible to calculate at any moment in time the composition of atmospheric moisture storage of all grid cells. Figure 4 illustrates this by showing snapshots, every twenty days, of the amount of moisture of continental origin as a fraction of total atmospheric moisture. It starts at the beginning of the modelled period and illustrates how the model spins up: in the first snapshot the stocks are still low. In the subsequent snapshots it can be seen how the ‘bulbs’ of continentally evaporated water move over time.

The regional moisture recycling ratios (at a 2.5° x 2.5° grid) and the continental precipitation recycling can be calculated directly over the full model grid. Not that the continental evaporation recycling ratio has to be calculated cell by cell. Although not illustrated, the calculation of moisture recycling ratios over larger regions than one grid cell has to be calculated region by region. Also, note that the residual factor is only used in the water balance for the continental precipitation recycling, conserving the ratio of continental vs. total atmospheric moisture from the previous time step (Yoshimura et al., 2004). This means that at every time step the moisture storage of continental origin plus the moisture storage of oceanic origin sums up to 100 % of the total atmospheric moisture storage. The sum of the residuals over a day and all continental areas averages out to almost zero, thus not disturbing the total water balance. However, a large residual factor can locally influence the results of regional moisture recycling and continental evaporation recycling strongly because these are ‘single cell’ calculations. Therefore, we have not used the residual factor in these calculations.

According to Burde and Zangvil (2001a) and Fitzmaurice (2007) there are three common assumptions in (the classical) bulk recycling models: (1) the use of time-averaged data, (2) the neglect of the atmospheric storage term, and (3) the well-mixed assumption. Our model does not suffer from the first two assumptions, since we have used time-accumulated data and the atmospheric moisture storage term is taken into account. We only makes use of the third assumption, that of a well-mixed atmosphere.

Lettau et al. (1979), Burde (2006) and Fitzmaurice (2007) have built models with incomplete vertical mixing. However, the question which values to use for the parameters that account for incomplete vertical mixing in these models remains difficult to answer. Estimations of the recycling not using the well-mixed assumption might also be done by taking a more complex modelling approach such as the use of GCM water vapour tracers (e.g. Koster et al., 1986, Numaguti, 1999, Bosilovich et al., 2002). Next to complexity itself, the drawback of such an approach is the use of model based data, which is more uncertain than the assimilated data obtained from reanalysis.
Fitzmaurice (2007) concluded that the well-mixed assumption (a) underestimates regional precipitation recycling in case precipitation stems from convection, (b) overestimates regional precipitation recycling in case of upper level storms, where energy and moisture is derived from outside the region, and (c) is probably valid for regions and periods which experience frequent deep convection such as the monsoonal period in Thailand. For the continental moisture recycling ratios in Figs. 6 and 7, this would a priori mean a small shift in the upwind direction for category (a), a small shift in the downwind direction for category (b), and validity in case precipitation is of category (c). Besides, we believe the question which physical water particle exactly is being recycled is not very relevant for this study. High relative humidity levels in atmospheric layers from which the precipitation does not stem can still play a role in ‘triggering’ precipitation.

3 Results and discussion

3.1 Regional moisture recycling

To illustrate the effect of scale on the regional moisture recycling ratios in Eqs. (2) and (5) we performed a case study on the continent of South America. Table 1 shows the regional recycling ratios for different scales. Obviously, the values increase when larger areas are chosen. For the Amazon region, which has often been of interest in recycling studies, our estimate of 29 % for the regional precipitation recycling ratio is slightly higher than the 25 % estimated by Brubaker et al. (1993) and Eltahir and Bras (1994) (using ECMWF data). Our estimate is in line with the GCM water vapour tracer study of Bosilovich and Chern (2006), but lower than the 41 % found by Burde et al. (2006), who did not invoke the well-mixed assumption of the atmosphere. Additionally, we present estimates of the fraction of evaporation which recycles within the same region; for the Amazon region this value appears to be 43 %.

However, the exact values of regional recycling are of little use as they do not describe the full hydrological cycle and the mechanism of moisture feedback over the continent. In reality, the atmosphere is not bound by grid cells with a certain dimension, nor is it bound politically or hydrologically. Thus, it is better is to look at regional recycling ratios qualitatively rather than quantitatively. Moreover, we think it unwise to draw conclusions on the importance of the continental moisture feedback and of the climatic sensitivity to land-use changes based on regional recycling ratios only, as many people have done in the past, because of the arbitrary choice for area size and shape. In Sect. 3.2 we describe the patterns of continental moisture recycling in detail, but first we take a qualitative look at regional moisture recycling.

Figure 5 shows the annual average regional precipitation and evaporation recycling ratio on the 2.5° latitude × 2.5° longitude model grid. Bearing in mind that the scale of a grid cell depends on latitude, the pattern of this map compares well to the results of Trenberth (1999) and Dirmeyer and Brubaker (2007). As mentioned before, regional recycling ratios are scale-dependent, thus the exact values of the recycling ratios are of little matter here. The results are interpreted as an indication of where the regional moisture feedback mechanism is significant. High regional recycling ratios can be observed over very wet areas, such as the tropical forests of South America, Africa and Southeast Asia. It can also be seen that the precipitation recycling over the Caspian Sea and the North American Great Lakes is slightly higher compared to the surrounding grid cells, indicating immediate feedback from areas where the evaporation is not limited by moisture availability. Furthermore, regional recycling is especially high in mountainous areas or just upwind of those areas. This effect is very obvious near the Andes, the Tibetan Plateau, the mountain ranges of south Africa and the Great Rift Valley in East Africa. To a lesser degree, the orographic effect on regional evaporation recycling can be observed near the Rocky Mountains, the mountains of Norway and the mountains near Turkey.

3.2 Continental moisture recycling from a new perspective

To assess the importance of continental moisture feedback we need to know the dependency, of any location, on upwind continental evaporation to sustain precipitation. Figure 6 presents the continental precipitation recycling ratio, as defined in Eq. (7) for every location in the world. This map compares well to similar maps shown by Bosilovich et al. (2002) and Yoshimura et al. (2004), albeit that the map shown by the latter does not represent an annual average. However, knowing the origin of precipitation alone cannot describe the full recycling process. Figure 7 shows the continental evaporation recycling ratio, as defined in Eq. (10). It can be interpreted as the importance of evaporation in any location to sustain downwind precipitation.

By definition both the continental precipitation and evaporation recycling ratios are scale-independent. Together they fully describe the continental moisture feedback within the hydrological cycle. The major source regions for continental precipitation can be observed in Fig. 7: the west of the North American continent, the entire Amazon region, central and East Africa and a very large area in the centre of the Eurasian continent. The areas that are major sinks for continually evaporated water (Fig. 6) are
situated north-east of North America, the Bolivia-Paraguay-Uruguay region, central and West Africa and large areas in China, Mongolia and Siberia. The areas east of the Andes, the Congo and the Tibetan Plateau are hotspots where both continental moisture recycling ratios are high. Apparently, it is difficult for moisture to leave these regions and regional recycling is a major source of precipitation.

In North America Fig. 6 indicates that oceanic sources are dominant over continental moisture recycling. In the West, where about 60 % of the evaporation returns to the continent downwind (Fig. 7), the absolute evaporation is however low compared to the precipitation in the East (see Fig. 3). Nonetheless, recycling is not negligible; over most of the continent, annual average precipitation relies for about 40 % on recycled moisture.

South America shows three distinct patterns in moisture recycling. The first pattern that can be observed is the evaporation from the Guianas and the Amazon region that is transported downwind to the Río de la Plata basin where it precipitates. This is in line with the conceptual model of this pattern that was presented in Marengo (2006). The second pattern is the local recycling just east of the Andes. Our hypothesis is that evaporated moisture in that region is repeatedly advected towards the Andes and almost all water precipitates due to orographic lifting. The third pattern is observed in Patagonia where very little to no moisture recycling takes place.

From Fig. 6, it is clear that the Indian Ocean is a major source of precipitation in East Africa. From here and from central Africa almost all the evaporation is recycled regionally or transported to West Africa. In the latter region the continental precipitation recycling plays a major role, which was confirmed by Njitchoua et al. (1999) who studied isotopic compositions of rainfall in the Cameroon rainforest. The Sahel, which often has been an area of research in the context of moisture recycling, receives its moisture (in)directly from three large water bodies, the Mediterranean Sea, the South Atlantic Ocean and the Indian Ocean. On average about 50-60 % of the precipitation originates from continental evaporation. This estimate is in line with the GCM water vapour tracer study of Koster et al. (1986), but lower than the 90 % estimate of Savenije (1995). This is probably caused by the fact that the latter neglected atmospheric moisture leaving the area. Furthermore, our estimate is much higher than the 35 % estimated by Brubaker et al. (1993) as recalculated by Eltahir and Bras (1996). We think this difference is mainly caused by using the regional precipitation recycling ratio rather than the continental precipitation recycling ratio. Besides, the differences with the studies of both Savenije (1995) and Brubaker et al. (1993) are also caused by the fact that these only took into account the South Atlantic Ocean as moisture source. Moreover, note that an exact comparison is difficult because slightly different study areas were chosen in these studies.

Between Europe and Asia the moisture flux is mainly eastward. This is reflected in the increase of the precipitation recycling ratio in eastward direction. By the time the moisture reaches western China, the original oceanic moisture only accounts for about 10-20 % of the precipitation. This is in line with the findings of Numaguti (1999), Serreze and Etringer (2003) and Stohl and James (2005), who also indicated recycling to be a major contributor to precipitation over Siberia, Mongolia and China. The importance of recycling can also be seen in the continental evaporation recycling ratio, which shows that on average 40-75 % of the evaporation from any region in Europe returns to a continental area. A hotspot where the regional moisture recycling is high is the area around the Tibetan Plateau. Tian et al. (2001), Yu et al. (2007) and Liu et al. (2008), who studied the isotopic compositions of rainfall in this area, also indicate regional recycling to play a major role around the Tibetan Plateau. The average moisture flux from any direction is mainly towards the region, and because of the altitude the total atmospheric moisture storage is low. Thus, this creates favourable conditions for subsequent moisture feedback.

Finally, in the south of India, Southeast Asia, and Oceania, the average fraction of the precipitation originating from continental evaporation is small. However, in the northern part of Australia, Indonesia and Papua New Guinea, which are very wet areas, the fraction of the evaporation returning to the continent is 40-70 %. A priori, we think this indicates a fast regional recycling process, but since so much oceanic moisture is present as well, the contribution of recycling to the total precipitation remains small.

### 3.2.1 Increase of fresh water resources due to continental evaporation


Another way of looking at the importance of continental moisture recycling is by defining the continental precipitation recycling multiplier (Savenije, 1995). For this definition it is important to realise that precipitation according to Eq. (6) consists of two components. We define the continental precipitation recycling multiplier as:
\[ m(t, x, y) = \frac{P}{P_a} = 1 + \frac{P_e}{P_a} \cdot \frac{1}{1 - P_e} \] (11)

The multiplier has physical meaning; it is amplification of precipitation due to continental evaporation. Its value has to be seen as a lower limit because the actual precipitation triggered by continental evaporation is higher due to the non-linear relation between precipitation and precipitable water, as was first speculated by Savenije (1996b). When integrated over a year and all continental areas the continental precipitation recycling multiplier is also the average number of times a water particle has sequentially fallen on the continent.

The recycling ratios and the multiplier per continent are presented in Table 2. It shows the significance of continental evaporation. On average, 38% of all precipitation is derived from continental sources and 52% of all evaporation returns to a continental area. This implies that there is at least 61% more precipitation on the continent than in the hypothetical case where there is no continental feedback at all. Thus, the precipitation is amplified by 1.61 on average, but in South America, Africa and Asia, continentally recycled moisture plays an even more important role.

A huge difference between the regional and continental evaporation recycling ratio can be observed in Europe. On the other hand, in Asia there is a big difference between the regional and continental precipitation recycling ratio. This proves that Europe is a large source of moisture for precipitation in Asia. Note that over the entire continental area, by definition, the regional moisture recycling ratios equal the continental moisture recycling ratios. The global continental moisture cycle is illustrated in Fig. 8, where \( F_h \) denotes horizontal atmospheric moisture flux and \( \sum F_w \) is continental runoff.

### 3.3 Seasonal variations of the continental moisture budget

This section presents the continental moisture recycling in January and July over the continents of South America, Africa and Eurasia. These are the continents where the continental moisture feedback mechanism plays a key role in the climate. From the seasonal variations it can be observed that recycling is most dominant in summer, when continental evaporation is high.

#### 3.3.1 South America

Figures 9 and 10 represent the moisture recycling patterns in South America in January and July. In January the precipitation is very high over almost the entire continent. About 60 to 80% of the precipitation falling in the Río de la Plata basin originates from continental rather than oceanic sources. Following the arrows that indicate the horizontal moisture fluxes it can be observed that this recycled precipitation is supplied by the Amazon basin, from which about 100 mm evaporation per month returns to the continent. Just east of the Andes, the total continentally recycled precipitation is up to 200 mm/month, which represents 40 to 80% of the total precipitation.

During the Southern Hemisphere winter, the pattern of moisture recycling is similar but has shifted to the North. In July, the water evaporated in the Guianas and the northern Amazon region is the most important for sustaining precipitation in the middle of the continent. In both January and July, evaporation in the northern part of the continent plays a major role in downwind precipitation. Enhancing runoff in this area could potentially be disastrous for the fresh water resources of the Bolivia-Paraguay-Uruguay region.

#### 3.3.2 Africa

In Africa the shift of the Intertropical Convergence Zone (ITCZ) is mainly responsible for the shift in rainy seasons. The implications for the moisture recycling patterns are shown in Figs. 11 and 12. In January, moisture recycling takes place mainly in the southern half of the continent where continental evaporation recycling is about 80 mm/month. Following the arrows representing the horizontal moisture flux, water is recycled from East Africa towards central Africa, where the continental feedback is responsible for 50 to 70% of the precipitation.

In July it can be observed that Africa’s rainforest is the major contributor to total precipitation in the wet areas. Almost all water that evaporates from the centre of the continent returns as continental precipitation. This is indicated by continental evaporation recycling ratio which is up to 100% in this region. The rivers in West Africa as well as the rivers springing from the centre of the continent, including the Nile, derive 30 to 70% of their water from continentally recycled precipitation. The Congo can be identified as the major source region of precipitation on the continent. Evaporation recycling in the Congo is 80 mm/month in January and more than 100 mm/month in July. This highlights the vulnerability of Africa’s climate to land-use changes in its rainforest.
3.3.3 Eurasia
From Figs. 13 and 14 it can be observed that moisture recycling in Eurasia varies considerably over the seasons. In January (Fig. 13) continental moisture feedback is a far less dominant process than it is in July. However, it is striking to see that even in January about 40 to 70% of the precipitation in China is derived from recycling over the Eurasian continent. In January, China’s main rivers (the Yellow River, the Yangtze and the Pearl River) are fed by sources of continental evaporation over eastern Europe and western Asia (by looking at the evaporation recycling ratio) and a source region covering Burma and Thailand (by looking at absolute evaporation recycling).

In July (Fig. 14) continental moisture recycling is an extremely significant process over the Eurasian continent. Note that the average moisture flux is still mainly eastward. In western Europe, the continental precipitation recycling ratio is already about 30%, which indicates transport of moisture with a continental origin from North America (see also Figs. 2 and 4) or from eastern Europe in case the wind is coming from the East. Furthermore, almost all the continental evaporation returns to the continent, which can be observed by the fact that the map of continental evaporation recycling is almost identical to the map that shows total evaporation, and of course the continental evaporation recycling ratio which is overall very high, 80 – 100% over most of the continent. As a consequence, continental moisture feedback accounts for 70 – 90% of the precipitation falling in an area ranging all the way from eastern Europe to the Pacific Ocean and from the Arctic ocean to the north of India.

4 Conclusion: what goes up must come down
The aim of this study is to understand how continental precipitation and evaporation interact. In western Europe, being close to the ocean, it is a widespread belief that all precipitation is derived from oceanic sources. From this perspective, it is considered highly unlikely that continental evaporation plays an important role in the occurrence of precipitation and the very idea that it does seems counter-intuitive. However, a close examination of the global topography and climate (Figs. 2 and 3) and of the continental moisture recycling patterns presented here (Figs. 6 and 7) offers new insight into the importance of the continental moisture feedback mechanism. Globally we found that 38% of the continental precipitation originates from continental evaporation and 52% of every water drop evaporated from a continent returns as continental precipitation (Fig 8).

We can conclude that continental moisture recycling plays an important role in the global climate. In this study we have identified hot spots which have a large regional recycling. Land-use changes in these areas can immediately affect the regional climate. In general, regional recycling is more significant in wetter areas but can be greatly enhanced by topography. Mountain ranges can play an important role in moisture recycling either by ‘blocking’ moisture from entering the continent (e.g. the Rocky Mountains and the Great Rift Valley) or by ‘capturing’ the moisture from the atmosphere to enhance continental recycling (e.g. the Andes and the Tibetan Plateau).

Moreover, we have identified regions which are strongly dependent on continental evaporation for the occurrence of precipitation, as well as the major moisture sources for these regions. In North America, moisture recycles from the West towards the East where on average up to half of the precipitation can originate from continental evaporation. In South America the evaporation from the Guianas and the Amazon appears to be the key factor in sustaining precipitation downwind in the Rio de la Plata basin. In Africa, we have seen that the Congo is a major supplier for Africa’s fresh water resources. We conclude that deforestation of these tropical forests can potentially lead to desertification elsewhere on the continent. Finally, we have observed a strong eastward increase of the continental precipitation recycling ratio over the Eurasian continent. This indicates the importance of recycling to sustain precipitation in Siberia, Mongolia and China. From the different recycling patterns in January and July we can conclude that a positive feedback mechanism exists in the summer, where continental evaporation leads to subsequent precipitation. This can most obviously be observed from the differences in recycling in Eurasia (Figs. 13 and 14).

In this paper we have stressed the fact that all water that evaporates eventually precipitates: what goes up must come down. Although this is popular knowledge, in hydrology this idea is not at all mainstream. In most hydrological modelling studies, evaporation is considered a mere loss to the system never to be returned. The same holds for precipitation; it is often considered an external forcing variable. For many basin-scale studies this approach is sufficient, but we have shown that a direct feedback mechanism exists. Recycled moisture on average multiplies our fresh water resources by 1.61, but locally this can be up to three times (e.g. the Bolivia-Paraguay-Uruguay region), and even more than tenfold in western China. Moreover, as we have shown, almost all evaporation from East and central Africa returns to the continent. Thus, we can conclude that draining any wetlands in the Nile basin (Mohamed et al., 2005) may slightly increase the discharge of the Nile, but will lead to a reduction of Africa’s total fresh water resources.

Based on our results, we think that decreasing the evaporation flux, e.g. by means of deforestation in a region where continental evaporation recycling is high, could result in droughts in downwind areas where overall precipitation amounts are
low. We suggest further research to be done on the climatic effects of land-use changes in regions, such as the Amazon and the downwind Río de la Plata basin where negative trends in precipitation, due to decreased recycling, may already be identifiable.

This study has identified the regions where continental moisture recycling plays an important role by supplying moisture, receiving moisture, or both. An interesting addition to this research would be to show global maps of typical travel distances and travel times of precipitated water (backward trajectories) and of evaporated water (forward trajectories). Previous moisture recycling studies have focused on the sources of precipitation only (e.g. Koster et al., 1986, Yoshimura et al., 2004, Bosilovich and Chern, 2006, Nieto et al., 2008). We suggest further research to focus on the destinations of evaporation as well. Potentially, our approach can be extended to calculate travel distances and travel times of atmospheric moisture.

Finally, it would be interesting to compute the differences in recycling of evaporation from transpiration, which is a productive flux, and evaporation from interception, the soil and open water, which are non-productive fluxes. Validation of our results can be done by performing a comparison between moisture recycling and stable isotope compositions in precipitation (see e.g. Salati et al., 1979, Njitchoua et al., 1999, Tian et al., 2001, Henderson-Sellers et al., 2002, Yu et al., 2007, Froehlich, et al., 2008 and Liu et al., 2008). Furthermore, based on the work of Joussamue et al., (1984) and Yoshimura et al. (2003), our approach can be extended by keeping account of stable isotope compositions.

Appendix A: Computational procedure

This appendix is an addition to the methods described in Sect. 2. Figure 15 gives an overview of the computational procedure. All boxes in orange are reanalysis data input, all blue boxes indicate calculations, the white boxes are output of the model and the green box represents an action. The arrows indicate in which sequence the calculations are performed. The upper part of the schematisation represents the part that calculates the atmospheric moisture storage and fluxes (see also Fig. 1) for each time step. The lower part of schematisation represents the part that does the actual water accounting plus the calculation of the recycling ratios. The time step is decreased from the 6-hour resolution of the input data to only 1 hour. In addition, the water accounting model is programmed to avoid negative storage and moisture fluxes higher than the storage to remain stable. The symbols have the following meaning:

\[ A = \text{area size (m}^2\text{)} \]
\[ E = \text{evaporation (m}^3\text{ s}^{-1}\text{)} \]
\[ E_a = \text{evaporated water that will be advected out of the region (m}^3\text{ s}^{-1}\text{)} \]
\[ E_{cel} = \text{evaporation of a certain cell (m}^3\text{ s}^{-1}\text{)} \]
\[ E_{con} = \text{continental evaporation (m}^3\text{ s}^{-1}\text{)} \]
\[ E_{reg} = \text{regional evaporation (m}^3\text{ s}^{-1}\text{)} \]
\[ F_a = \text{atmospheric moisture flux (m}^3\text{ s}^{-1}\text{)} \]
\[ F_{a,\text{i}} = \text{atmospheric moisture flux into a cell (m}^3\text{ s}^{-1}\text{)} \]
\[ F_{a,\text{o}} = \text{atmospheric moisture flux out of a cell (m}^3\text{ s}^{-1}\text{)} \]
\[ g = \text{gravitational acceleration (m s}^{-1}\text{)} \]
\[ L = \text{length of a cell parallel to the wind flux (m)} \]
\[ lat = \text{latitude (°)} \]
\[ lon = \text{longitude (°)} \]
\[ P = \text{precipitation (m}^3\text{ s}^{-1}\text{)} \]
\[ p = \text{pressure (Pa)} \]
\[ p_s = \text{surface pressure (Pa)} \]
\[ q = \text{specific humidity (kg kg}^{-1}\text{)} \]
\[ S_a = \text{atmospheric moisture storage, calculated statically (m}^3\text{)} \]
\[ S_{a,\text{cel}} = \text{part of the atmospheric moisture storage which has the origin of a certain cell (m}^3\text{)} \]
\[ S_{a,\text{con}} = \text{part of the atmospheric moisture storage which is from continental origin (m}^3\text{)} \]
\[ S_{a,p} = \text{partial atmospheric moisture storage between certain pressure levels (m}^3\text{)} \]
\[ S_{a,\text{reg}} = \text{part of the atmospheric moisture storage which is from regional origin (m}^3\text{)} \]
\[ S_{a,w} = \text{atmospheric moisture storage calculated by water balance (m}^3\text{)} \]
\[ t = \text{time (s)} \]
\[ U = \text{zonal wind (m s}^{-1}\text{)} \]
\[ V = \text{meridional wind (m s}^{-1}\text{)} \]
References


Tables and figures

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<tr>
<th>Region</th>
<th>ρr (%)</th>
<th>εr (%)</th>
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<td>centre: 7.5° S, 62.5° W</td>
<td>7</td>
</tr>
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<td>5° × 5° grid cell</td>
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<td>11</td>
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<td>Bolivia</td>
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<td>Amazon</td>
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<td>South America</td>
<td>(11.25° N – 53.75° S, 81.25° W – 36.25° W)</td>
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Table 1: Annual average regional moisture recycling ratios at different scales on the continent of South America for the period Sep. 1997 – Aug. 2002.

<table>
<thead>
<tr>
<th>Region</th>
<th>ρr (%)</th>
<th>εr (%)</th>
<th>ρc (%)</th>
<th>εc (%)</th>
<th>mc (‐)</th>
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<td>North America</td>
<td>(76.25° N – 13.75° N, 141.25° W – 56.25° W)</td>
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<td>South America</td>
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<td>(76.25° N – 36.25° N, 8.75° W – 61.25° E)</td>
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<td>27</td>
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<td>62</td>
</tr>
<tr>
<td>Asia</td>
<td>(76.25° N – 6.25° N, 61.25° E – 146.25° E)</td>
<td>36</td>
<td>50</td>
<td>48</td>
<td>55</td>
</tr>
<tr>
<td>Oceania</td>
<td>(6.25° N – 46.25° S, 98.75° E – 176.25° E)</td>
<td>15</td>
<td>28</td>
<td>18</td>
<td>29</td>
</tr>
<tr>
<td>All Continents</td>
<td>(76.25° N – 53.75° S, 180° W – 180° E)</td>
<td>38</td>
<td>52</td>
<td>38</td>
<td>52</td>
</tr>
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</table>

Table 2: Annual average moisture recycling per continent. Note that the oceanic masses within the study area are not considered in the regional recycling and by definition also not in the continental moisture recycling. The results presented in this table are for the period Sep. 1997 – Aug. 2002.

Figure 1: Conceptual presentation of wind, humidity and horizontal moisture flux profile in the atmosphere.
Figure 2: Global topography: height above Mean Sea Level, major rivers, coastline and annual average wind field between the ERA-40 reanalysis 850 and 925 hPa pressure levels for the period Sep. 1997 – Aug. 2002.

Figure 3: Annual average precipitation and evaporation over continental areas for the period Sep. 1997 – Aug. 2002.
Atmospheric moisture of continental origin as a fraction of total atmospheric moisture

Figure 4: Daily average atmospheric moisture of continental origin as a fraction of the total moisture storage.

Annual Average Regional Moisture Recycling

Figure 5: Annual regional precipitation and evaporation recycling ratio within a 2.5° latitude × 2.5° longitude grid cell for the period Sep. 1997 – Aug. 2002.
Figure 6: Annual average continental precipitation recycling ratio for the period Sep. 1997 – Aug. 2002.

Figure 7: Annual average continental evaporation recycling ratio for the period Sep. 1997 – Aug. 2002.

Figure 8: Water balance of all continental areas in percent normalised to the precipitation for the period Sep. 1997 – Aug. 2002.
Figure 9 – Figure 10: South America: Moisture recycling in January and July. Precipitation \( P \), evaporation \( E \), continentally recycled precipitation \( P_c \), continental evaporation that returned to the continent \( E_c \), continental precipitation recycling ratio \( \rho_c \), continental evaporation recycling ratio \( \varepsilon_c \). The arrows indicate the vertically integrated moisture flux field.

Figure 11 – Figure 12: Africa: Moisture recycling in January and July. Precipitation \( P \), evaporation \( E \), continentally recycled precipitation \( P_c \), continental evaporation that returned to the continent \( E_c \), continental precipitation recycling ratio \( \rho_c \), continental evaporation recycling ratio \( \varepsilon_c \). The arrows indicate the vertically integrated moisture flux field.
Figure 13: Eurasia: Moisture recycling in January. Note that the colour scale of this figure is different than that of Fig. 14. Precipitation $P$, evaporation $E$, continentally recycled precipitation $P_c$, continental evaporation that returned to the continent $E_c$, continental precipitation recycling ratio $\rho_c$, continental evaporation recycling ratio $\varepsilon_c$. The arrows indicate the vertically integrated moisture flux field.
Figure 14: Eurasia: Moisture recycling in July. Note that the colour scale of this figure is different than that of Fig. 13. Precipitation $P$, evaporation $E$, continentally recycled precipitation $P_c$, continental evaporation that returned to the continent $E_c$, continental precipitation recycling ratio $\rho_c$, continental evaporation recycling ratio $\epsilon_c$. The arrows indicate the vertically integrated moisture flux field.
Figure 15: Schematisation of the water accounting model.